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Procedia Engineering 5 (2010) 564–567

Procedia Engineering

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Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Millimeter wave detection by thermopile antenna

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Abstract

In this paper a novel MEMS thermopile structure is proposed, which consist of linearly arranged p- and n- type polysilicon strips instead of the conventional loop-like configuration. It is shown that these devices sense the millimeter wave radiation beyond the infrared. The polarity and frequency dependence of the sensitivity prove that these strips behave as absorbing antennas towards the microwave/millimeter wave radiation. The induced current is calculated having a maximum in the geometrical center of the antenna, exactly at the position where the hot end of the thermopair is located. The measured responsitivities to direct heating, infrared radiation, 13 GHz microwave radiation and 100 GHz millimeter-wave radiation are presented.

Keywords: Millimeter wave, THz, Thermopile, Antenna

1. Introduction

Recently THz and mm wave radiations find widespread application, albeit their management is more difficult than that of microwaves. A serious bottleneck is the lack of choice of appropriate detectors. Even the best microwave Schottky diodes have their cut-off frequency within these bands. Micromachined thermopiles are widely exploited for measuring physical quantities, which can be converted to temperature difference. Examples are: detection of infrared radiation via heating of an absorber [1], realization of functional thermal circuit by direct electrical heating [2], or even gas flow sensing by cooling the electric heater [3], etc. Regarding the THz and mid-infrared radiation the thermopiles were used only for the read-out of the temperature increment caused by absorption

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doi:10.1016/j.proeng.2010.09.172

of the radiation in the feed-point resistance of the metallic antenna [4], or in the thin-film absorber [5]. We have proposed a more compact solution that operates at room temperature [6]. The thermopile itself is the antenna and the induced current heats up its body mostly in the vicinity of the hot end of the thermopairs. This function is enabled by the geometrical conversion shown in Fig.1. The linearly arranged thermopairs constitute a series of short-circuited dipole antennas.

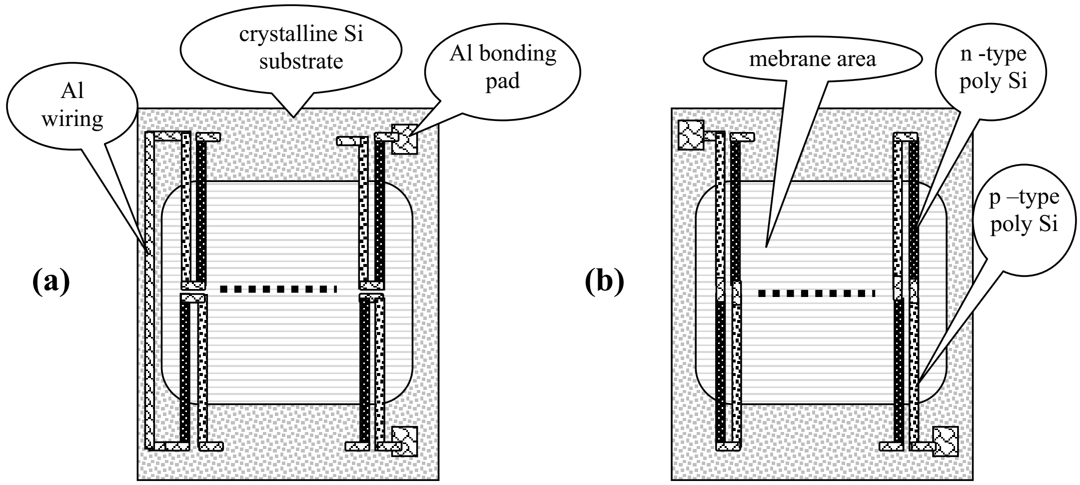

Figure 1. (a) A conventional thermopile consist of serially connected loops composed of two thermoelectric materials, suitably of p- and n – type polycrystalline silicon. As the infrared radiation is absorbed, the central part will heat up, because the membrane has high heat resistance, while the outer ends of the strips are kept at the substrate temperature (b). The schematics of the proposed linear arrangement of thermopairs.

2. Theory

To determine the current distribution in this structure, a reasonable simplified model is required. First the current distribution is calculated in one semiconductor line, cross-talk effects by the other lines are neglected. This can be an acceptable approximation to get an insight into the system behavior. Moreover, the rectangular cross section of the semiconductor strip is converted to a cylindrical wire. The cylindrical conductor has the same length as the original; its radius is about the half of the width of the original strip. Such a cylindrical antenna can completely be described by the Pocklington or the Hallen integral equation. To solve these equations, preliminary assumptions about the excitation are needed. We consider a plane wave with the incident field strength parallel to the longitudinal axis of the thermopair. It is also important to note that the semiconducting strip is not a perfect conductor. While its conductivity falls in the range of $10^2 \ldots 10^5$ S/m, and on the other hand the conductivities of the metals used in the microwave technique are generally in the range of 10^7 S/m. This value plays a role in the description of the internal impedance per unit length needed also in the integral equations [9]:

$$z_1 = \frac{1}{\pi a_g^2 \sigma_1} \qquad (1)$$

, here σ_1 is the conductivity of the thermopile, and a_e is the electrically equivalent radius of the cylindrical antenna. It has to be mentioned that z_1 is equal to the DC resistance of the antenna, because the equivalent radius is significantly smaller than the skin depth. The conductivity, propagation constant and the wave impedance of the surrounding medium are denoted by σ_2, k and z_2, respectively. Based on [9, 10], the current distribution on a resistive antenna immersed in a homogeneous medium can be obtained as follows:

$$I_x(x) = K_1(\cos k_c x - \cos k_c h) + K_2(\cos 0.5kx - \cos 0.5kh) \quad (2)$$

where

$$k_c^2 = k^2 - i\frac{4\pi k}{z_2 c_1} z_1 . \quad (3)$$

C_1,K_1,K_2 are constants depending mainly on the geometry of the antenna and the frequency of the incident wave, while their dependence on σ is rather weak. x is the distance measured along the antenna in both directions from the center point to ±h, i.e. the half length of the antenna. k_c is the complex propagation constant, with a strong dependence on *k*. It can be seen that with the increase of the frequency, the real part grows quadratically, while the imaginary part increases only linearly. Therefore at high frequencies, such as 100 GHz or above, the imaginary part of the complex propagation constant becomes negligible compared to the real part. The antenna acts as if it were a perfect conductor, although it is obviously not. In other words, the complex propagation constant is equal to the propagation constant of the surrounding medium, and the p- and n- doped strips have essentially the same propagation constant. To obtain the distribution, consider that there are two regions, where we have to perform the calculations:

- one is over the membrane – where the surrounding medium is practically air, and
- the other one is over the substrate, which can be considered as a microstrip line, immersed in a medium characterized by the effective permittivity.

Both regions could be calculated by using the appropriate constants in the expression (2). The current distribution has to be continuous at the interface of both regions, and the current has to vanish at the ends of the antenna. With these restrictions one can obtain the current distribution on the thermopair as follows:

$$\begin{aligned} I_x(x) = &\left[H(x) - H(x-h_0)\right]\left[D_1\left(\cos(k_a x) - \cos(k_a h_0)\right) + D_2\left(\cos(0.5k_a x) - \cos(0.5k_a h_0)\right) + I_0\right] + \\ &\left[H(x-h0) - H(x-h)\right]\left[E_1\left(\cos(k_s x) - \cos(k_s h_0)\right) + E_2\left(\cos(0.5k_s x) - \cos(0.5k_s h_0)\right)\right] \end{aligned} \quad (4)$$

Here H(x) is the Heaviside step function. It is used in order to match the two distributions at the interface of the regions; k_a and k_s are the wavenumbers over the membrane (air) and over the substrate, respectively; D_1, D_2, E_1 and E_2 are complex coefficients. The normalized distribution of the square of the current is shown in Fig.2.

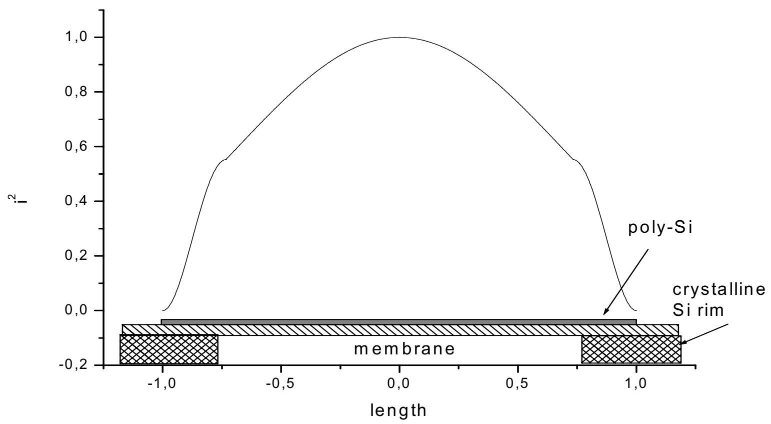

Figure 2. Distribution of the square of the current along the antenna.

3. Experimental results and discussion

Details of sample preparation and measurements were published earlier [6]. Both the loop-like and the linear thermopiles were manufactured and characterised. Further thermopiles with Al in one arm (p-Si/Al and n-Si/Al) were also fabricated. Four types of measurements were performed on the devices. The responsivity against direct heating was investigated on loop-like structures with a built-in heater on the membrane. The infrared responsivity was also measured with a heated black body as a source. No significant difference was observed between the behavior of the linear and the loop-like structures. It should be stressed that neither an absorbing layer, nor any focusing element was applied on the chips. The responsivities in the microwave and millimeter wave bands were measured in the K_u-band, at 13 GHz and in the W band at 100 GHz. The polarity dependence was very significant at both frequencies. The maximum output was obtained with the E field parallel to the lines. The reading in the orthogonal case dropped, however, to the level of the background noise. We have to point out that neither the loop-like structures, nor the thermopiles having Al in one arm did produce in these measurements any significant output. They both were, however, sensitive for the infrared.

Table 1 summarizes the measured responsivities. In case of electric heating all the power is introduced directly into the thermopile, close to the hot point resulting in highest responsivity. Infrared radiation will only partially be absorbed and uniformly distributed across the surface. The responsivity at 100 GHz is reasonably larger than at 13 GHz. This fact proves the antenna-like operation of the device: a 1.6 mm long antenna should have a resonance at around 100 GHz, while at 13 GHz it acts as a short dipole with low efficiency.

Table 1. The measured responsitivities in V/W*

structure	direct electric heating	IR Thermal radiation	13 GHz	100 GHz
loops	90	20	0	0
linear	-	20	0.2	5.6

*It should be noted, that the absorbed IR and microwave power was not exactly determined from measured reflected and transmitted power.

Acknowledgements

This work was supported by the Hungarian Research Found (OTKA) under contract No: 77843, 77997 and 73424NK. The measurements at 100 GHz were performed at the Universität Duisburg-Essen. The kind help and contribution of Dr. Vitaly Rymanov and Prof. Andreas Stöhr is acknowledged.

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